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Application of Ferroelectrics in Low-Cost Microwave Phased-Array Antennas

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ABSTRACT

A novel, low-cost, phased-array antenna that uniquely incorporates bulk phase shifting using voltage-tunable dielectric (VTD) material is presented. The array does not contain an individual phase shifter at each radiating element. This paper presents the antenna concept and describes how it can be used as a low-cost phased array. The VTDs that are used in this antenna are described. The measured antenna patterns of a prototype phased array demonstrating electronic beam scanning at 10 GHz are also presented.

INTRODUCTION

A phased-array antenna can rapidly scan its beam without mechanical movement. Each radiating element of a phased array is usually connected to a phase shifter or a transmit/receive (T/R) module, which determines the phase of the signal at each element to form a beam at the desired angle. The most commonly used phase shifters are the ferrite and diode varieties. The phase shifters or T/R modules with their control circuitry along with the array feed network account for the major hardware cost in a phased-array antenna. A typical array may have several thousand elements and that many phase shifters or T/R modules; hence, it is very expensive. Therefore, reducing the cost and complexity of the phase shifters or T/R modules and their control circuitry is an important consideration in the design of phased arrays.

The concept of the novel antenna described in this paper has been published elsewhere [1]. We call it the ferroelectric lens phased-array antenna. It uniquely incorporates bulk phase shifting using voltage-tunable dielectrics (VTDs); the array does not contain an individual phase shifter at each element. The number of phase shifters are reduced from (n × m) to (n + m), where n is the number of columns and m is the number of rows in a phased array. The number of phase shifter drivers and phase shifter controls is also reduced by the same factor using row-column phase control. This can potentially lead to low-cost phased-array antennas.

An ideal application for the ferroelectric lens is a semiactive tactical missile seeker [2]. Rapid beam switching can advance missile seeker capability including forward looking guidance-integrated fusing and tracking in shorter range.

In this paper, we review the ferroelectric lens concept. We describe the bulk VTD ceramics that we used. We present experimental results of a small column of the lens at X band (8-12.5

GHz). Radiation patterns of a prototype phased array demonstrating electronic beam scanning at 10 GHz are also presented.

DESCRIPTION OF THE FERROELECTRIC LENS

The main feature of the antennas that use VTD is the change of dielectric constant (ε_r) with an applied dc bias voltage. A lens type antenna is discussed in this paper. Figure 1 shows a dielectric lens made-up of dielectric slabs sandwiched between conducting plates. Dielectric slabs are VTDs whose dielectric constant can be changed by applying and varying the dc electric field (dc voltage sources V_1, V_2...V_n are used for this purpose, as shown in Fig. 1). If a plane wave is incident on one side of the lens with RF electric field $\boldsymbol{E}$ normal to the conducting plates, the beam coming out on the other side of the lens can be scanned in the $\boldsymbol{E}$-plane if a linear phase gradient is introduced along the $\boldsymbol{E}$-plane direction by adjusting the voltages V_1, V_2...V_n. The corresponding dielectric constants are shown as ε_{r1}, ε_{r2}...ε_{rn}, in Fig. 1.

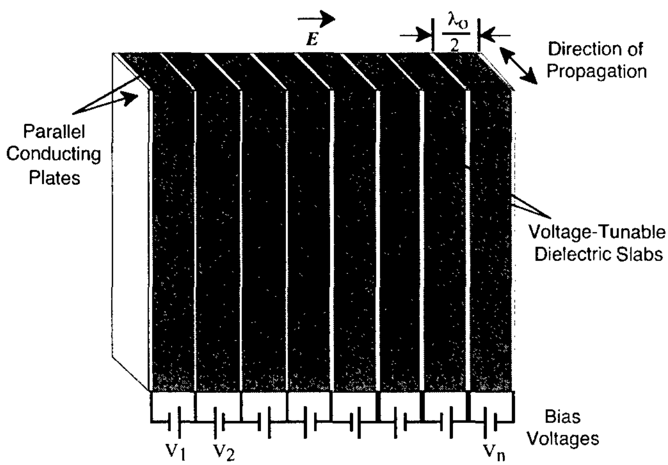

Figure 1. Basic configuration of the ferroelectric lens.

Figure 1 is used to illustrate the principle of operation of a ferroelectric lens. However, it has some limitations. To reduce the lens complexity and weight, the number of dc bias voltages and the number of conducting plates need to be minimized. This can be achieved by selecting the separation between the conducting plates to be slightly less than $\lambda_o/(1+\sin\phi_s)$, where λ_o is the free space wavelength, and ϕ_s is the maximum scan angle; this separation is the maximum allowed to avoid grating lobes. Normally, the space between the conducting plates would be less than $\lambda_o/2$ to assure that only the dominant transverse electromagnetic (TEM) mode propagates. However, in a ferroelectric lens, this space is filled with a high dielectric constant VTD, and so the space between the plates is much larger than $\lambda/2$, where λ is the wavelength in the VTD. This means that higher-order modes may propagate. To avoid problems with higher-order modes that may be excited, the spacing between the conducting plates should be reduced to less than $\lambda/2$. In addition, there should be some type of impedance matching arrangement to match the lens surface to free space.

Figure 2 shows a practical lens configuration. This configuration has several advantages over the basic configuration of Fig. 1. Each column of the lens is a parallel-plate waveguide, as shown in Fig. 2 (b). The separation between the parallel-plates at the input and output of the waveguide is $\lambda_o/2$. This separation is reduced using a step of height *h*. The center section of the column is filled with VTD material, which is bisected with a center bias plate such that the thickness of each VTD piece is less than $\lambda/2$; this eliminates higher-order mode propagation. The center bias plate halves the thickness across which the dc bias voltage is applied thus halving the maximum bias voltage requirement. The use of the center bias plate also allows the parallel plates to be at ground potential. This makes the handling of the lens safer. Quarter-wave dielectric transformers are used for impedance matching the input and output (empty) waveguide sections to the center (VTD-loaded) waveguide section. The dielectric constants of these transformers are between that of air (ε_r=1) and of the VTD (ε_r~81).

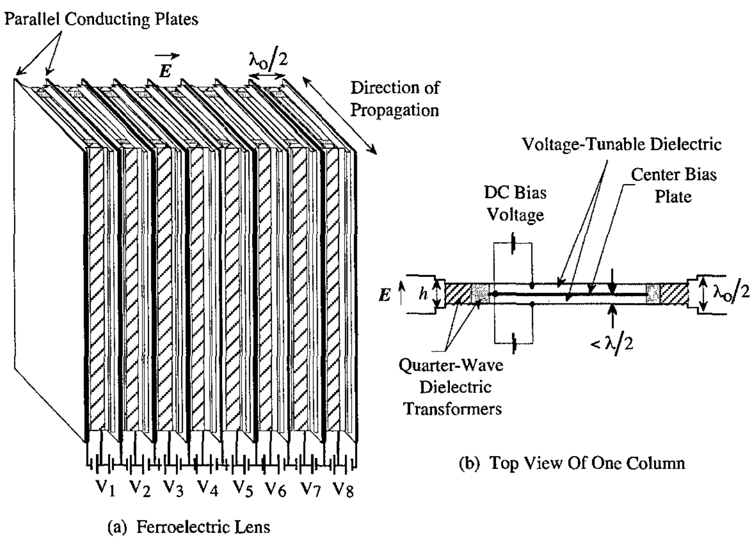

Figure 2. A practical configuration of the ferroelectric lens.

For electronic beam scanning, the VTD must provide 360° differential phase shift. The length of the VTD needed (in the direction of propagation) to obtain 360° differential phase shift is [1]

$$l = \frac{\lambda_o}{\sqrt{\varepsilon_{rmax}} - \sqrt{\varepsilon_{rmin}}} = \frac{\lambda_o}{\sqrt{\varepsilon_{rmax}}\left[1 - \sqrt{1 - \text{tunability}}\right]} \tag{1}$$

where ε_{rmax} is the dielectric constant when no bias voltage is applied, and ε_{rmin} is the dielectric constant when maximum dc bias is applied. The dielectric constant of a VTD decreases as the bias voltage increases. Tunability is the fractional change in the dielectric constant; it is defined as

$$\text{Tunability} = \frac{\varepsilon_{rmax} - \varepsilon_{rmin}}{\varepsilon_{rmax}}. \tag{2}$$

Also, it can be shown [1] that in order to obtain 360° phase shift, the dielectric loss through a low-loss VTD is

$$\alpha\,(\text{dB}) = \frac{27.3\ \tan\delta}{1 - \sqrt{1 - \text{tunability}}} \tag{3}$$

where tan δ is the loss tangent of the VTD.

In general, VTDs with larger ε_r (we will use ε_r to denote the dielectric constant with no bias voltage applied) offer higher tunability; both larger ε_r and higher tunability are desired to reduce the lens size. However, the lens impedance matching and fabrication tolerances are easier with smaller ε_r. Therefore, a compromise is a VTD with $\varepsilon_r = 81$ and tunability of 24% at a bias field of 8 V/μm. From Eq. (1), we can show that the length of VTD needed to obtain 360° differential phase shift is less than λ_o (e.g. 3 cm at 10 GHz). From Eq. (3), it can be shown that for a VTD that has 24% tunability, tan δ must be 0.0047 to limit the loss due to the VTD to 1 dB, which is our goal. At 10 GHz, tan δ of the VTD that we used is 0.007.

PHASED-ARRAY CONFIGURATIONS USING FERROELECTRIC LENS FOR 2-D SCANNING

A single ferroelectric lens provides one-dimensional (1-D) electronic beam scanning. Two-dimensional (2-D) beam scanning can be achieved by cascading two ferroelectric lenses or using one ferroelectric lens in a hybrid configuration with a phased array that can scan the beam in one plane [1].

Figure 3 shows the cascading of two spatially orthogonal ferroelectric lenses. The first lens provides an elevation scan of a vertically polarized wave. A passive 90° polarization rotator then rotates the RF electric field to become horizontally polarized. The second lens then provides the azimuth scanning of the horizontally polarized wave. In Fig. 3, a non-scanning planar array is shown as the illuminator (or feed) for the dual lenses. A space feed can also be used with the dual lens configuration, as shown in Fig. 4. In this configuration, in addition to scanning the beam, row-column phase controls can also be used to correct the spherical phase errors due to the point space feed. However, this phase correction is not exact, but it is satisfactory for many applications.

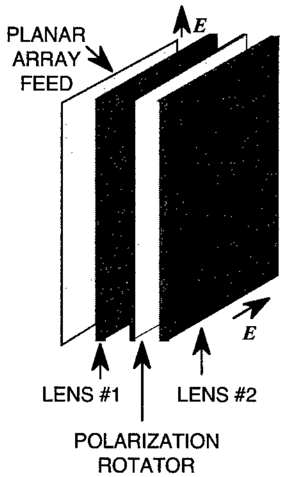

Figure 3. Dual lens configuration with a planar array feed.

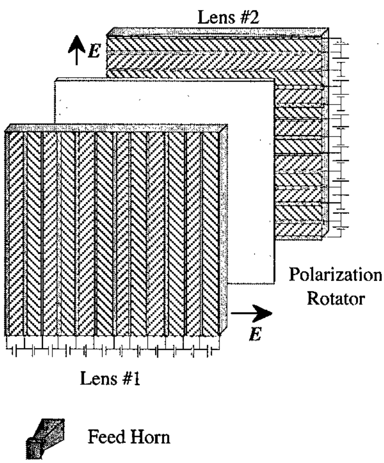

Figure 4. Dual lens configuration with a space feed.

Another method of achieving 2-D beam scanning uses a hybrid technique in which a planar array with phase shifters scans the beam in one plane and the ferroelectric lens scans the beam in the other plane. For example, as shown in Fig. 5, a slotted waveguide array with phase shifters provides electronic beam scanning in the azimuth plane. Electronic beam scanning in the elevation plane is obtained by placing a ferroelectric lens in front of the slotted waveguide array.

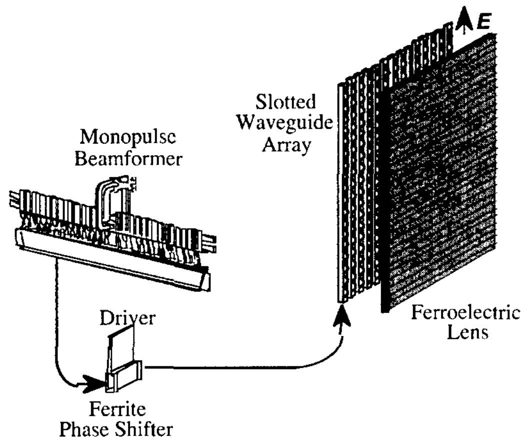

Figure 5. Hybrid phased array configuration for 2-D scanning.

VOLTAGE-TUNABLE DIELECTRICS

VTDs that we used are bulk composite ceramics of tunable ferroelectrics in the paraelectric phase and non-tunable materials [1,3]. In addition to providing bulk phase shift, VTDs offer reciprocal phase shift; i.e., the transmission coefficient through devices that use these materials is the same for different directions of propagation. Ferroelectrics are inherently broadband. That is, they do not have a low frequency limit like ferrites. Until the development of these bulk composites, the large ε_r and tan δ of ferroelectric materials excluded them from being used at microwave frequencies. VTDs can be manufactured in bulk, thick film and thin film forms. Only bulk ceramics are suitable for the ferroelectric lens because of the physical size and power handling requirements.

There are many known ferroelectrics. The ferroelectric in the VTD that we used was Barium Strontium Titanate, (BST), specifically $Ba_{0.55}Sr_{0.45}TiO_3$. BST is the most widely used ferroelectric at microwave frequencies. We are interested in applications at X band. Experiments were conducted at X band with a VTD whose ε_r and tan δ were 81 and 0.007, respectively at 10 GHz. Tunability was a respectable 24% at a bias of 8 V/μm. Curie temperature, T_c, was -75°C, which means that the BST is in the paraelectric phase at room temperature. T_c is controlled not only by the Ba:Sr ratio, but also by the amount of the non-tunable material that is added. Using Eq. (3), the loss due to the VTD for obtaining 360° differential phase shift was calculated to be 1.5 dB at 10 GHz.

EXPERIMENTAL RESULTS

Lens columns have been designed, built and tested at C band (4-8 GHz) and X band. Figure 6 shows the experimental setup with one column of the lens. A Network Analyzer is connected to a rectangular waveguide through a coax-to-waveguide transition. The width of the waveguide is flared to create an ***H***-Plane horn, which feeds the parallel plate column. The network analyzer measures the s-parameters of the column as a function of frequency and dc bias voltage.

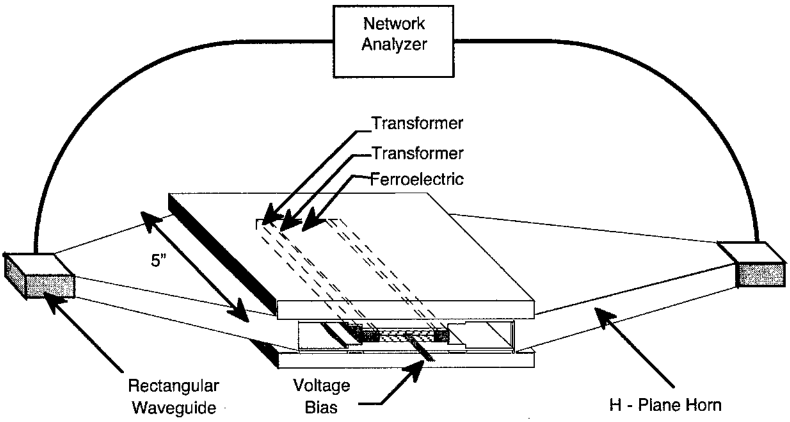

Figure 6. Experimental setup for one column.

At X band, the largest VTDs that we have used were 2.54 cm long (in the direction of propagation), 0.13 cm high and 12.7 cm wide [1]. Figure 7 shows the measured voltage transmission and reflection coefficients of a small lens column at X band when the dc bias is zero. This column included VTD whose ε_r and tan δ are 81 and 0.007, respectively, at 10 GHz. The transmission coefficient is inversely proportional to frequency. This is due to two reasons. First, tan δ increases with frequency; second, the electrical length (in terms of wavelengths) of the VTD in the direction of propagation increases with frequency since the physical length is kept constant (2.54 cm). The wideband impedance matching design that we have developed provides very low reflection coefficient over the broad frequency range of 8-12 GHz. The measured voltage reflection coefficient is less than 0.22, which corresponds to a voltage standing wave ratio (VSWR) of less than 1.6. The reflection coefficient does not increase as dc bias is applied to decrease the VTD's ε_r [1]. Figure 8 plots the measured differential phase shift at several frequencies as a function of the dc bias. As expected, the phase shift is fairly linear with frequency and dc bias. We have obtained more than 360° differential phase shift at 12 GHz at a dc bias of 8 V/μm. Using the measured data shown in Fig. 7, the loss due to the VTD can be calculated. This loss is plotted in Fig. 9 as a function of frequency. The loss is about 1.8 dB at 10

GHz, and it is proportional to frequency. The measured loss agreed well with theoretical prediction.

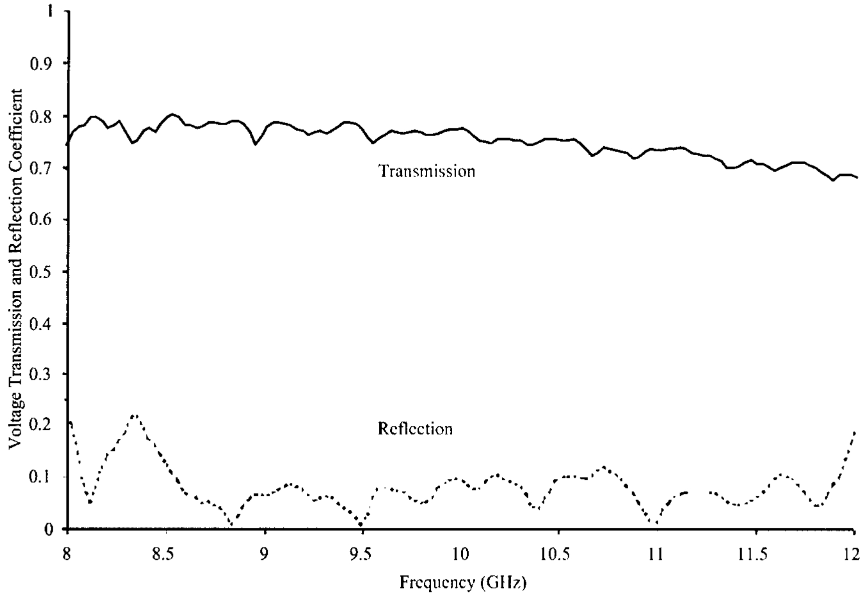

Figure 7. Measured voltage transmission and reflection coefficient of a lens column.

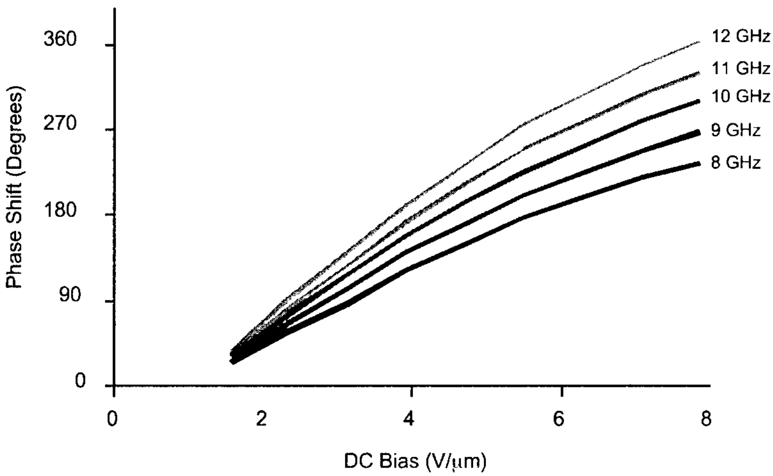

Figure 8. Measured differential phase shift at X band.

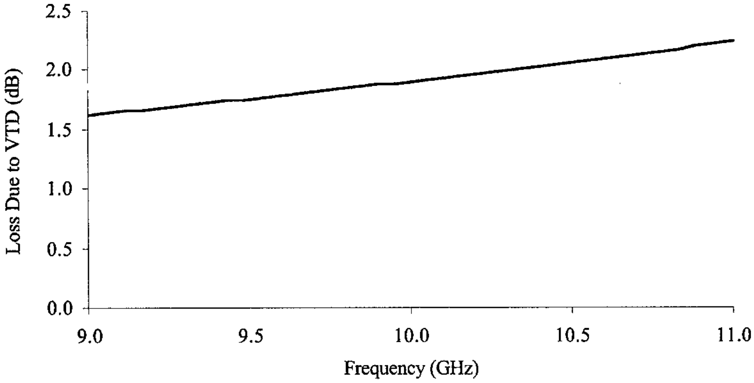

Figure 9. Measured loss due to the VTD at X band.

A two-column interferometer and a 3-column lens have been built and demonstrated at the Naval Research Laboratory. The radiation patterns of these phased arrays were measured. Electronic beam scanning was demonstrated at X band. There was no indication of any material inhomogeneity in the patterns.

For the tactical missile seeker application, a 12-column lens was built and demonstrated at Raytheon [4]. The pattern was measured as dc bias was applied to each column to scan the phased-array antenna pattern. Fig. 10 shows the prototype antenna in an antenna test chamber. In Fig. 11 four of the measured patterns are plotted for 10 GHz frequency. Electronic beam scanning was again demonstrated; the beam clearly scanned to 60°.

PLANS

A ferroelectric lens phased-array antenna has been demonstrated at X band. There is strong interest to operate missile seekers at higher frequencies, especially Ka band (27-40 GHz). At these frequencies, wide frequency bandwidths and narrow antenna beamwidths can be achieved. Presently, we are developing two different ferroelectric lens phased arrays at Ka band. One architecture is based on the designs described in this paper, which were conceived at NRL. Another architecture which is under investigation at Raytheon may provide 2-D scanning with one lens. Compared to the NRL architecture, the design and manufacturing of this architecture would be complicated but the loss might be less. The results of these investigations will be published at a later time.

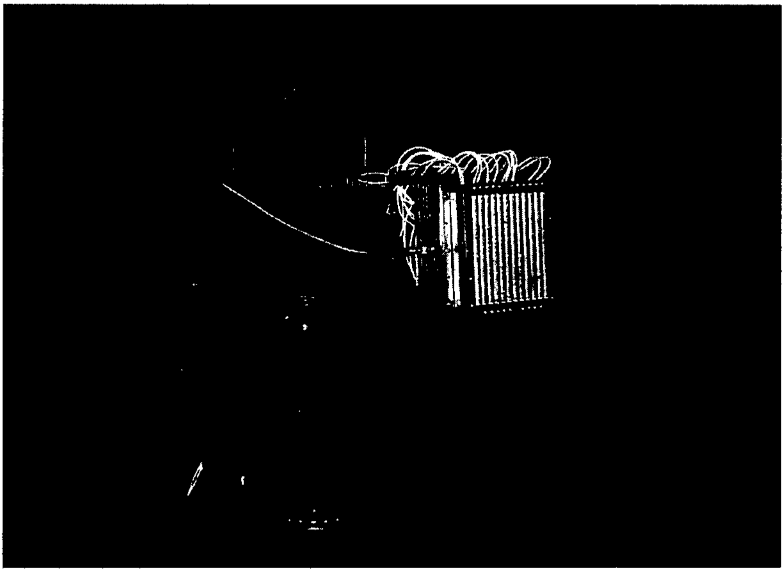

Figure 10. Prototype ferroelectric lens.

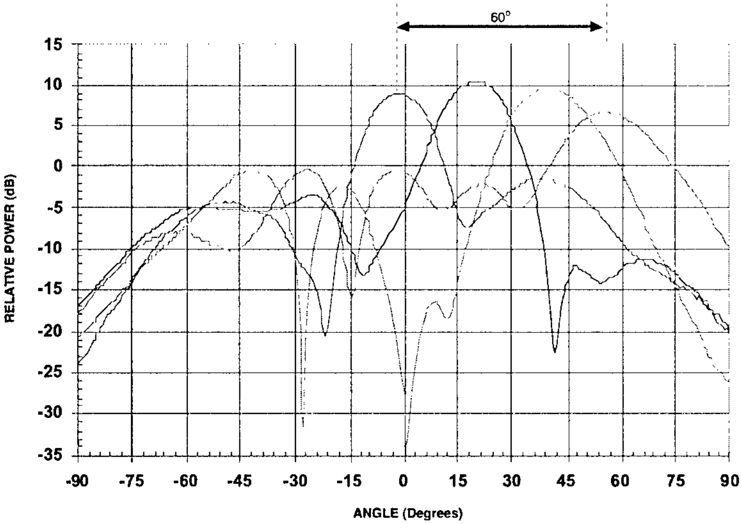

Figure 11. Measured radiation patterns of the prototype ferroelectric lens at 10 GHz for four different scan angles.

SUMMARY

The work done so far in developing the ferroelectric lens, a low-cost, phased-array antenna, was reviewed. The VTD ceramics that we used provide 360° differential phase shift with about 2 dB loss at 10 GHz. Electronic beam scanning has been demonstrated in a prototype ferroelectric lens at 10 GHz. Work is continuing in reducing the loss in the dielectrics.

ACKNOWLEDGMENTS

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